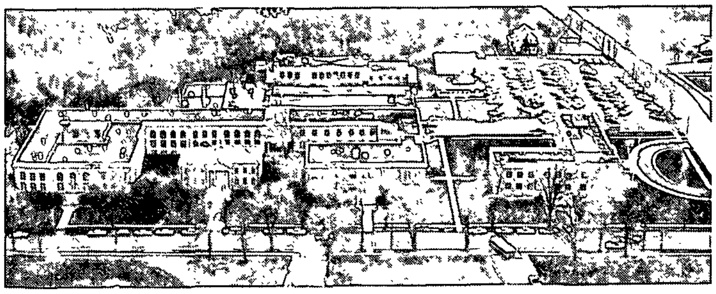

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EMPIRICAL RELATIONSHIPS BETWEEN TISSUE SOFTNESS AND OUT-OF-PLANE ULTRASONIC MEASUREMENTS

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Empirical Relationships Between Tissue Softness and
Out-of-Plane Ultrasonic Measurements

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ABSTRACT

In this paper, out-of-plane ultrasonic velocity and attenuation testing (1) is introduced for use on tissue. These measurements (along with in-plane extensional stiffnesses, basis weight, ZD compressibility, and caliper measurements) are conducted on a group of commercial tissue samples. Panel rankings for "bulk softness" and "surface softness" are also performed. Empirical correlations between the physical parameters and subjective softness rankings are examined. The three parameters which provide the best combined linear correlation to the softness rankings are the ultrasonic impedance, the mass specific ultrasonic attenuation, and the basis weight. Using these three quantities, the combined regression coefficients squared, r^2, are 0.884 for bulk softness and 0.785 for surface softness. When the facial tissues and bathroom tissues were analyzed separately, the r^2's are 0.997 and 0.970 for bulk softness and 0.971 and 0.896 for surface softness. Acoustic impedance is the most significant factor in the overall and facial tissue correlations, while specific attenuation is most significant when the bathroom tissues were analyzed alone.

Introduction

Softness is historically defined in terms of the subjective perceptions of a panel of human beings. It is basically a tactile perception, but panelists can also be influenced by such things as sample size, ply number, color, smell, and sound of crumpling (2-8). Softness, therefore, is an ill-defined, complex function of a multitude of physical and psychological interactions (3-5). Softness can be divided into bulk softness and surface softness (4,5). Bulk softness is normally judged by hand crumpling the tissues, while surface softness tests can be conducted by a light brushing of fingertips over the tissue surfaces (4,5).

The perception of softness is, of course, related to the physical properties of the tissue. Apparent density, basis weight, flexural rigidity, ZD compressibility, and surface smoothness all influence softness (9). These properties are closely related to the fundamental structures and the mechanical properties of fibers such as flexural rigidity of individual fibers, fiber length, the fiber bonding level and the distribution of the bonding inside the sheet. Flexural rigidity is the parameter most widely used in bulk softness correlations (4,8-11), while the magnitude and the distribution of surface irregularities appear to be more important in surface softness analysis (4,5).

There are several methods for performing the subjective panel assessments. These include magnitude estimation (3), multidimensional scaling (12), and pair-comparison techniques (3). Pair-comparison panel assessments, which are the simplest techniques, can be made by scaling, rating, or ranking the samples. The scaling and rating methods extract more information, but the panelists must be specially trained to assure repeatable results. The pair-comparison ranking method is used in this study.

Many people have studied the implications of tissue softness using subjective and instrumental approaches (3-22). It is generally agreed that the subjective assessments are necessarily tedious and time-consuming and are unduly influenced by human factors. For these reasons, numerous attempts have been made to develop instrumental techniques which, at least partially, supplant the ranking panels. Some of the methods [the Clark stiffness tester (13), the Brown method (14), the Peirce tester (15), and the torsion pendulum method (7)] are suitable for evaluating bulk softness. Others [the surface softness analyzer (5,6) and the Kato surface friction tester (16)] attempt to quantify surface softness. The Handle-O-Meter (17,18) is sensitive to a combination of surface and bulk properties. In spite of these worthy efforts, panel assessments remain the most commonly-used methods for tissue softness quality control.

The purpose of this paper is to introduce the use of ultrasound for measuring out-of-plane properties in tissue. In order to arouse interest by demonstrating a potential for practical application, the results are presented in terms of their correlations with panel softness rankings. Ultrasonic tests are rapid, nondestructive, and may have future application on-line. However, it is well understood that ultrasonic techniques (like the other instrumental approaches to softness) cannot reproduce or replace the panel tests. A more fundamental study is necessary to determine the effects of furnish and process variables on the propagation of ZD ultrasound through tissue, but, in the meantime, here are the softness correlations.

Experiment

As described in Table I, seven commercial bathroom tissues and seven commercial facial tissues were used for this study. From each of the 14 kinds of tissue samples, eight single specimens were selected. The two-ply sheets were gently divided into single plies. Each sample was cut into a 4.5 x 8 inch rectangle for the panel testing. All testing was conducted in a room controlled at 50% R.H. and 73°F.

Table I here

The ultrasonic measurements were made using The Institute of Paper Chemistry's automated out-of-plane velocity tester (1). This is a computer-controlled apparatus which uses two specially developed, neoprene-faced, PVDF transducers to couple ultrasound into one surface of a paper board sample and detect it on the other face. The transducers are precisely aligned and mounted in a caliper gage (23). This allows simultaneous caliper and time-of-flight measurement at a repeatable time after contact of the neoprene face to the sample. A test sequence begins by placing a sample in the vertical gap between the two transducers. The computer (an IBM PC-AT® compatible) activates a motor that releases the top transducer, which becomes dead-weight loaded (50 kPa) to the lower one. After waiting a prescribed time for the neoprene to conform to the sample, one transducer is excited with a 1.5 MHz, single-cycle sine wave pulse. This produces a disturbance that propagates through the sample and into the other transducer. The resulting electrical signal is amplified, digitized at the rate of 100 MHz, and communicated to the computer. The computer calculates the cross-correlation function between this signal and one obtained during calibration from transit through a thin aluminum foil. The maximum in the cross-correlation function, along with the known transit time through the foil, allow the computer to determine the time-of-flight through the sample. This divided into the caliper (which is determined from the output of an

L.V.D.T.) is the time-of-flight velocity. The computer also performs a Fourier analysis of these signals, and it compares the foil and sample phases and amplitudes at each Fourier component.

Since paper strongly attenuates out-of-plane ultrasonic energy (especially at high frequency), it is difficult to generate pulses that are narrow compared to the ZD transit time through paper. This generally makes the apparatus inappropriate for testing low basis weight papers, as the transit time is less than the period of the pulse, and there is a danger of interference between multiple reflection at the sample-neoprene interfaces. For these reasons, the instrument was designed for operation on paperboard. However, it was later realized that if the loading pressure was lowered from 50 kPa to 20 kPa, meaningful measurements could be made on tissue. The ZD velocity of ultrasound in tissue is considerably lower than paper, and sufficiently long transit times are detected with a 20 kPa loading pressure.

The results of the ultrasonic time-of-flight measurements can be expressed in terms of several parameters. The velocity of sound (V_{ZD} = caliper/time-of-flight) is the most commonly used. However, the out-of-plane bulk elastic stiffness ($C_{33} = V_{ZD}^2$ multiplied by density) is also of interest. The ZD acoustic impedance of the sample, Z, is a third parameter. It equals the density multiplied by the velocity, which in terms of the measured quantities is simply basis weight divided by time-of-flight. This is a particularly appealing quantity, since it does not require a caliper measurement.

The amplitude results are presented in the form of an overall attenuation coefficient, A. In order to calculate A, the ratios of the amplitudes of the Fourier components through the foil signal to those through the sample signal are calculated. These ratios are weighted according to the squared amplitude through the sample and averaged. Then, A is defined as 20 times the base ten logarithm of the average.

The amplitude ratios are influenced by reflections at the transducer-sample interfaces, by viscoelastic dissipation in the sample, and by scattering from the fibrous structure. Assuming that the coupling between surfaces is perfect, reflection losses alone would cause the ratio of sample signal to foil signal to be $4Z_NZ/(Z_N+Z)$, where Z_N is the acoustic impedance of the neoprene front-face. This is already a small number, since Z_N is much greater than Z. Perfect coupling means that the sample and neoprene move in unison at the interface. This is far from accurate at tissue-neoprene interfaces loaded to 20 kPa, and real interfacial losses are greater than $4Z_NZ/(Z_N+Z)$. The other two phenomena produce bulk losses which are dependent on the basis weight. Experiments performed at 20 kPa on liner board samples, with progressive amounts of surface grinding, demonstrate that there is little dependence of A on basis weight. This is taken as evidence that for tissue at 20 kPa interfacial effects dominate the A parameter.

The softness rankings were performed by a panel of two men and four women. Ratings for bulk softness (by hand crumpling) and surface softness (by fingertip feel) were obtained using a pair-comparison method. The panel results were conducted as follows. Each panelist compared each pair of samples in a random order. A positive 1 was tabulated for the softer sheet, and a negative 1 was tabulated for the harsher one. If the two sheets were judged equal, 0 was recorded for both. The numbers were totaled for each sheet. The softness ranking was then obtained by adding a constant, which gives the harshest sheet a ranking of 1, to each total.

Tensile load-elongation tests were also made. These were performed using an Instron tensile tester following TAPPI Standard Method T 404 om-87 with cross head speed of 1 inch/min. Extensional stiffnesses were calculated from the initial slope of the load-elongation curves, and the geometric mean of the MD and CD numbers was recorded. Young's moduli in the MD and CD were also calculated (using the caliper measured with soft platens at 20 kPa) and recorded.

The final physical parameter measured was the ZD compressibility. This is defined as one minus the ratio of the soft-platen caliper at 20 kPa divided by the soft-platen caliper at 9 kPa.

Results

The panel softness rankings are given in the form of a column graph in Fig. 1. The agreement between individual panelist values was good. When regression analysis was performed with the ranking of the individuals and the average ranking, the lowest correlation coefficient was 0.871. A slightly higher correlation coefficient was obtained for crumpling than fingertip feeling, indicating that the bulk softness is more repeatable. From Fig. 1, it is clear that there is a strong positive correlation between the bulk softness and surface softness rankings. Notice also that the lotion treated sample (no. 9) ranked first in the bulk and surface panel testing and that the highly embossed tissue (no. 1) ranked better in the bulk test than it did in the surface test.

Figure 1 here

To give the reader a feeling for the range of the ultrasonic, time-of-flight measurements, a bar graph of the impedance calculations is presented in Fig. 2. Included in the impedance testing were some other paper types: a fine writing paper; a coated paper; a wax coated paper; a nonwoven rayon sheet; and three grades of linerboard. The additional samples provide a reference for the tissue impedances. By comparing Fig. 1 and 2, notice that softer tissues generally have lower impedances.

Figure 2 here

A bar graph is presented in Fig. 3 for the attenuation coefficients of the same samples. Since Z_N is larger than Z for all samples, interfacial reflection losses tend to increase with decreasing impedance, and some correlation between impedance and attenuation coefficients is expected. This is the case, but, by comparing Fig. 2 and 3, it will be noted that significant differences occur in the ordering of samples. It seems that the time-of-flight and amplitude measurements are contributing complementary information.

Table II is a list of the significance of the variance ratios (F-ratio) and correlation coefficients between softness rankings and individual physical properties. Notice that the ultrasonic parameters correlate better with softness than do the standard mechanical tests. It is particularly interesting that the high frequency ZD ultrasonic tests provide a much better correlation than the low frequency ZD compressibility tests, which are more directly related to the softness perception (9). The fact that there are good correlations between softness and a number of parameters which have some independent variation indicates that a multiple linear regression would be beneficial.

Table II here

In order to determine the physical tests that best account for the softness variations, a stepwise linear multiple regression analysis was conducted. Using a selection based on F-ratios, the combination of three parameters that gave the best linear fit were chosen. Table III shows the results for the bulk softness analysis. Here, the favored quantities are listed in the left column, while the others, along with the appropriate statistical information, are in the right column. The three optimum quantities are the impedance, the mass specific attenuation, and the basis weight - two ultrasonic parameters and a very basic mechanical property. The three combine to give an r^2 of 0.884 for bulk softness ranking, and 0.785 for surface softness ranking. Figures 4 and 5 are plots of the observed <u>versus</u> the predicted softnesses. Notice that points representing the embossed and lotion treated samples are relatively far from the line of one to one correspondence.

Table III and Figures 4 and 5 here

Table IV lists the regression parameters for bulk and surface softness and the three chosen parameters. Results are also given in Table IV for the regression analysis conducted separately on facial and bathroom tissues. When the two are treated separately, the squared correlation coefficients are 0.997 and 0.970 for bulk softness and 0.971 and 0.896 for surface softness. Notice, in Table IV, that the regression coefficients are quite different for facial and bathroom tissues. The facial tissues have a much larger coefficient for the impedance, and bathroom tissues have the larger specific attenuation coefficient. When multiple regression analyses were performed on the facial and bathroom tissues separately, the order of chosen parameters was Z, BW, A/BW for the facial tissues and A/BW, BW, Z for the bathroom tissues. It seems that A/BW plays a stronger role in bathroom tissues because of the greater surface effects, while Z is most important for creped facial tissues.

Table IV here

Conclusions

Out-of-plane ultrasonic time-of-flight and attenuation measurements can be applied to tissue grades. Using automated equipment developed at The Institute of Paper Chemistry, these tests are rapid, repeatable, and nondestructive. Over a range of commercially available samples, ultrasonic parameters correlate with subjective softness rankings. In fact, the ultrasonic tests are more highly correlated with softness than are the standard mechanical tests, conducted as part of this study. The use of a multiple linear regression with ultrasonic impedance (which is simply basis weight divided by time-of-flight), mass specific attenuation, and basis weight is demonstrated to be a simple and effective approach for predicting softness.

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Figure Captions

1. Softness rankings of commercial tissues.
2. Acoustic impedance of regular papers and tissues.
3. Attenuation coefficient of regular papers and tissues.
4. A plot of the predicted and measured bulk softness rankings.
5. A plot of the predicted and measured surface softness rankings.

I. Description of the tissue samples

Sample No.	Plies	Basis weight* kg/m^2	Type
1	1E	0.0248	B
2	1P	0.0292	B
3	2	0.0157	B
7	2P	0.0167	B
11	2	0.0218	B
12	2	0.0155	B
6	1	0.0419	B
4	2	0.0165	F
5	2	0.0155	F
8	2	0.0147	F
9	2L	0.0198	F
10	2	0.0143	F
13	2	0.0169	F
14	2	0.0145	F

E - highly embossed; L - lotion treated;
P - pattern printed.
B - Bathroom tissue; F - Facial tissue
* - Basis weight are all measured by a single ply.

II. Correlations between measured physical properties and both bulk and surface softness ranking

		Variance Ratio		Correlation Coefficient	
No.	Variables	Bulk Ranking	Surface Ranking	Bulk Ranking	Surface Ranking
1	Acoustic impedance	27.83	23.75	-0.836	-0.815
2	Mass specific attenuation coeff.	16.71	15.95	0.763	0.755
3	Basis weight	2.94	4.11	-0.444	-0.505
4	Tensile stiffness	5.54	5.92	-0.562	-0.575
5	Young's modulus	8.41	8.25	-0.642	-0.638
6	MD Young's modulus	8.09	7.86	-0.635	-0.629
7	CD Young's modulus	8.78	8.82	-0.650	-0.651
8	Out-of-Plane stiffness	13.06	14.45	-0.722	-0.739
9	Attenuation coeff.	4.75	2.52	0.532	0.417
10	Caliper	0.03	0.26	0.051	-0.144
11	Density	2.74	1.38	-0.431	-0.322
12	Time-of-flight	1.31	0.64	0.314	0.225
13	Out-of-plane velocity	1.98	2.88	-0.377	0.440
14	ZD compressibility	0.21	0.05	0.131	0.066

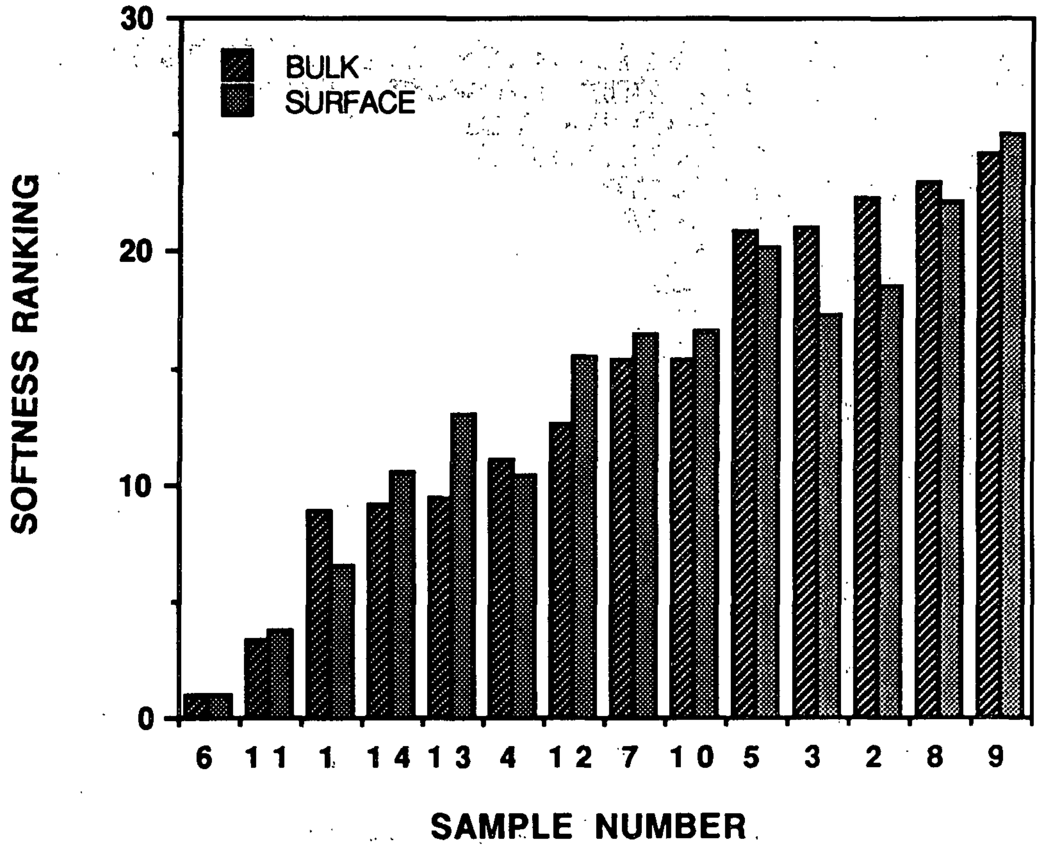
III. Bulk stiffness multiple regression analysis with stepwise selection of variables

$r^2 = 0.884$

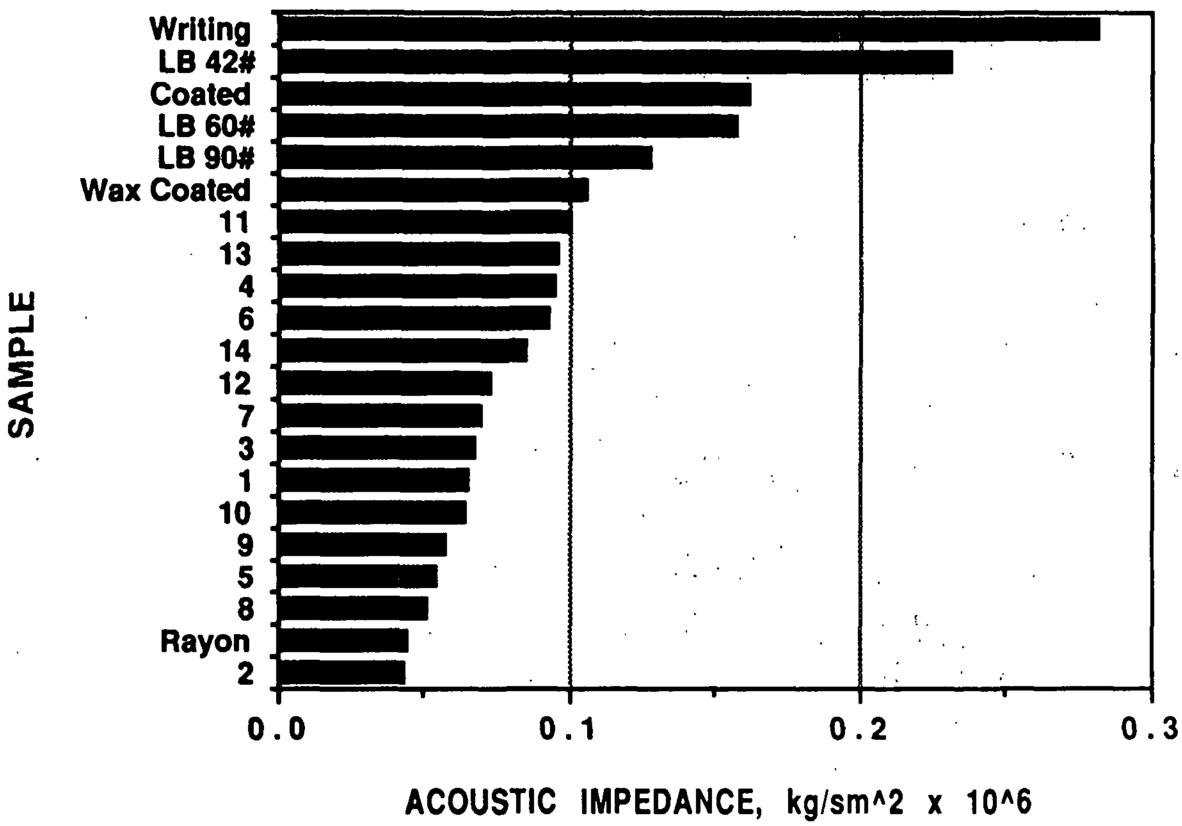
Variables in Model	Coeff.	F-Remove	Variables Not in Model	P.Corr.	F-Enter
1. Z	$-1.88\ m^2s/kg \times 10^{-4}$	10.06	4. E_{mean}	0.480	2.70
2. A/BW	$2.22\ m^2/kgdB \times 10^{-2}$	15.65	5. Et	0.433	2.07
3. BW	$6.66\ m^2/kg \times 10^2$	9.07	6. E_{md}	0.534	3.60
			7. E_{cd}	0.360	1.34
			8. caliper	0.378	1.50
			9. compressibility	0.053	0.03
			10. C_{33}	0.361	1.35
			11. time-of-flight	0.244	0.57

IV. Results of multiple regression analysis

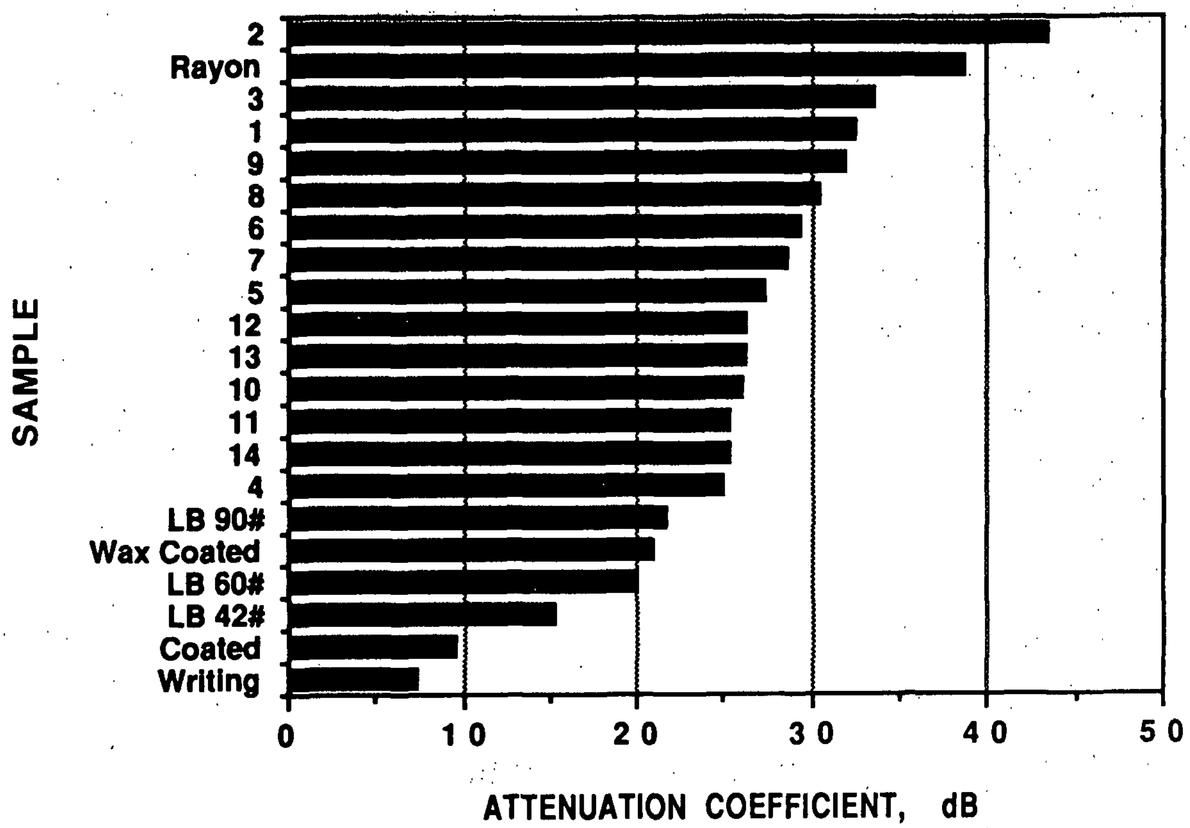
		Regression Coefficient				Correlation Coeff. of Multiple Regression (r^2)
		Z [$m^2s/kg \times 10^{-4}$]	A/BW [$m^2/kgdB \times 10^{-2}$]	BW [$m^2/kg \times 10^2$]	Constant	
Overall	Bulk	-1.88	2.22	6.66	-21.5	0.884
	Surface	-1.84	1.60	3.71	-6.1	0.785
Facial	Bulk	-4.42	0.12	5.94	30.5	0.997
	Surface	-4.12	-0.01	10.81	22.5	0.971
Bathroom	Bulk	-1.02	2.69	7.67	-36.5	0.970
	Surface	-0.93	1.97	4.37	-19.8	0.896



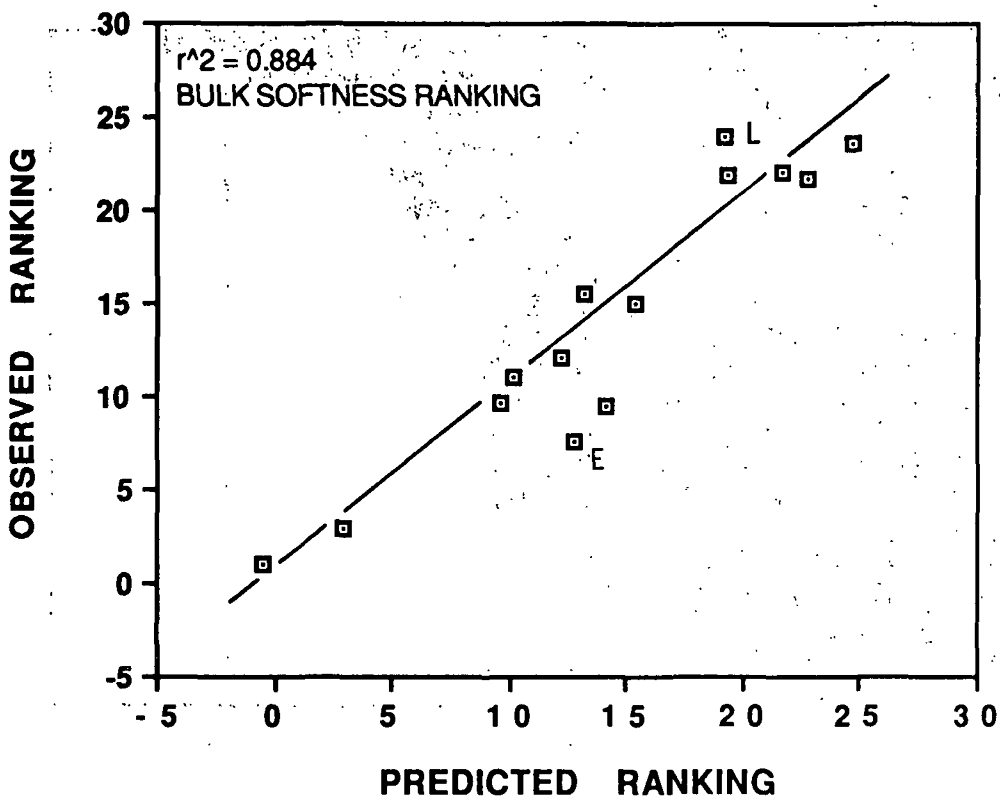
1. Softness rankings of commercial tissues.



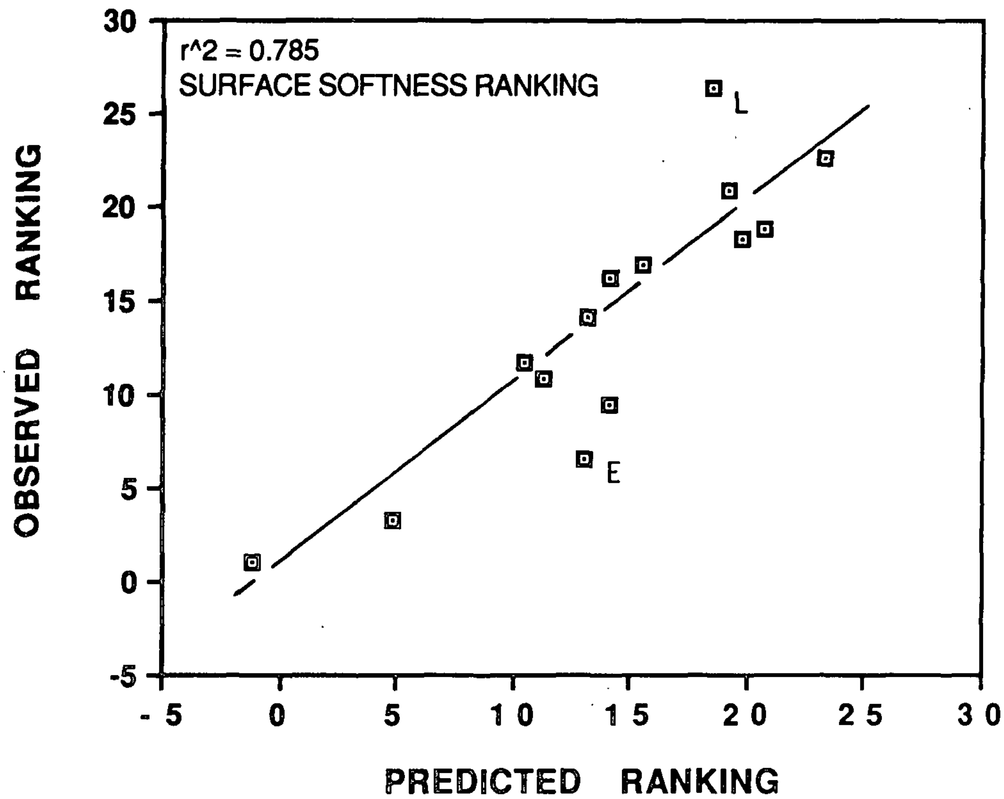
2. Acoustic impedance of regular papers and tissues.



3. Attenuation coefficient of regular papers and tissues.



4. A plot of the predicted and measured bulk softness rankings.



5. A plot of the predicted and measured surface softness rankings.